GAS TURBINES

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Summary

The use of electricity is a key issue in the development of today's human civilization. Since nuclear and hydro power plants are still playing a subordinated role and renewable energies are far away from being a major source of electricity, the majority of the world's electric energy is generated by power plants driven by the combustion of fossil fuels. Most of these power plants are operated with coal to heat up boilers and run steam turbines with the generated steam, but an increasing number is equipped with gas turbines, which burn oil or natural gas.

The main advantage of gas turbine driven power plants compared to coal fired ones is the much higher degree of environmental compliance. Due to the much better relation of hydrogen and carbon in oil and gas compared to any other fuel except of pure hydrogen, the emission of CO_2 per MW generated electricity is the lowest of all fossil fuel driven power plants, especially if the heat in the flue gas is recovered by a boiler and the

generated steam is used to drive a steam turbine. These combined cycle power plant offer the highest degree of efficiency that a power plant can provide today. In order to guarantee a flawless operation of such power plants, a new kind of control techniques had to be developed concerning the specific operation conditions of gas turbines and steam turbines. Using this combined cycle power plants are the first choice for a fast erected, cheap and reliable source of electricity.

1. Power Plant Setups

The power generation tasks of gas turbine driven power plants can generally be divided into two areas: base load and peak load operation. The intended type of operation the particular power plant is designed for, determines the general design of the *power block*, the combination of gas and steam turbines and their generators. This chapter is focusing on gas turbines and combined cycle power plants. Hence, steam turbines will only be addressed as parts of the latter.

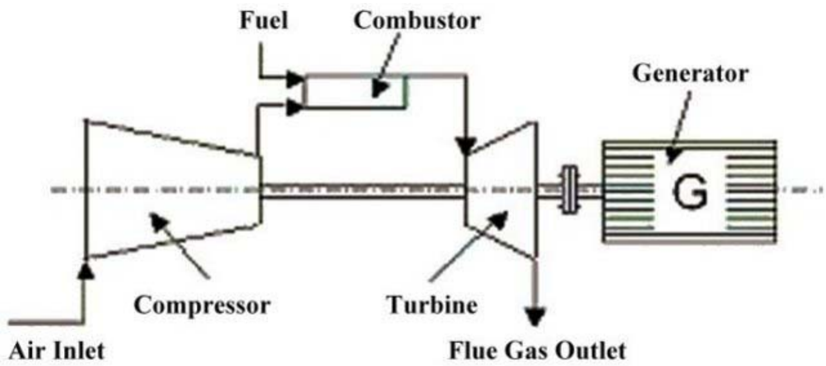

Figure1: Single shaft power block.

Figure 1 shows the setup for a typical, heavy-duty gas turbine driven power plant as it is often utilized for peak load applications, i.e. daily operation during times with highest power demand and price. Compressor, turbine and generator can be mounted on one common shaft or rotor or, for smaller turbines, linked by a gear. To start up the power block, the generator is commonly operated as a motor first. After a sufficient rotor speed is reached, the gas turbine is ignited and the power supply to the generator/motor is switched off.

The gas turbine accelerates further until it reaches its nominal speed. Now the generator is synchronized and connected to the power grid. The gas turbine is operated at constant speed to maintain a constant frequency at the generator output. Load changes are compensated by the adjustment of the fuel flow to the combustor.

This setup is the most simple and inexpensive from the mechanical point of view and is widely used; not only for small gas turbines of several hundred kW but also for machines of several hundred MW power output. But the design also has a couple of disadvantages. First, there is the long shaft, which has a low resonance frequency. This frequency is excited if the mass forces of the gas turbine and the generator are moved within certain speed range. Short shafts have a relatively high resonance frequency, which is reached only at very high speed. Especially power plant gas turbines do not reach these high-speed ranges due to their relatively low rotor speed, which is necessary for the synchronization with the power grid. But low frequencies, which are typical for long shafts, are already reached during startup. Thus, there are speed ranges, which have to be passed very fast.

Another disadvantage is the sensitivity with respect to fast load changes. If the load on the generator increases very fast, there is a danger of a compressor stall (see Section 2.2) due to a deceleration of the rotor. Depending on the size of the machine there are either bleed valves or adjustable compressor guide vanes or both installed to prevent this. On the other hand, the controller also has to be able to handle a fast decrease of the generator load to prevent the danger of turbine overspeed in case of part load or full-load shedding due to sudden loss of connection of the power plant to the electrical grid or within the electrical grid itself.

A better, but more expensive way to handle shaft resonance frequencies as well as load change responses is to divide the turbine, and hence the shaft, into two independent parts. The smaller high-pressure turbine is only coupled with the compressor and takes as much energy out of the combustion gas as it is necessary to drive the compressor. The low-pressure turbine is running free and provides the mechanical energy to drive the generator. Figure 2 shows such a setup.

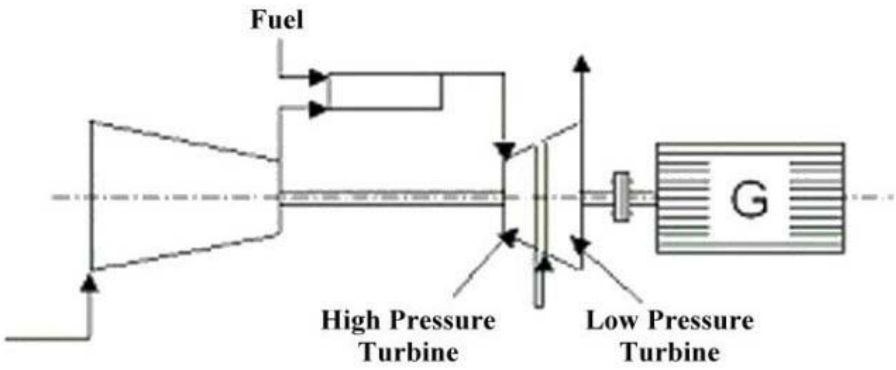

Figure 2: Two shaft, single cycle power block.

This type of gas turbine is operated with the objective to maintain a constant speed of the low-pressure turbine and, thus, the generator. The combination of compressor, combustor and high-pressure turbine, also called the *core engine*, works just as an independent gas generator, which has to provide the hot combustion gas to drive the low-pressure turbine. If fast load changes occur in this configuration, only the low-pressure turbine is influenced and the gas generator can go on operating with minor disturbance. The only requirement is a fast control loop to react immediately on the load changes.

Depending on the operating conditions and the type of gas turbine, the exhaust gas, leaving the last turbine stage, still has temperatures around 550°C and higher. To improve the total efficiency of the power plant this heat energy can be used to produce steam in a boiler. The steam can be used in additional industrial processes, for district heating or to drive a steam turbine. The last design is called a combined cycle power plant and has a much higher total efficiency than a single cycle power plant. Due to the more complex control technique and longer startup times this type of power plant is almost exclusively used for base load operations.

Especially in countries with weak grids and no nuclear or hydro power plants gas turbines are also operated for frequency support, stabilizing the grid frequency by modulating their power output to the grid.

The general setup of combined cycle power plants is to be divided in single shaft, double shaft and multi shaft installations. Single shaft combined cycle power plants are the most inert type of setup and are mainly used for base load applications.

Since the steam turbine is coming into operation only after heating up of the whole water/steam cycle, a freewheel clutch installed between the steam turbine and the generator prevents the gas turbine from spinning up the steam turbine in a cold steam cycle. Due to the freewheel clutch the shafts of the gas turbine and the steam turbine are spinning up separately, which prevents them from reaching speed ranges that would cause dangerous resonance frequencies.

As soon as the boiler is heated up to operation temperature the control valve is opened and the steam turbine is now providing its part of power to drive the generator. A few installations are using additional heat sources on the boiler to speed up the startup process. Figure 3 shows a single shaft, combined cycle setup without additional boiler heating.

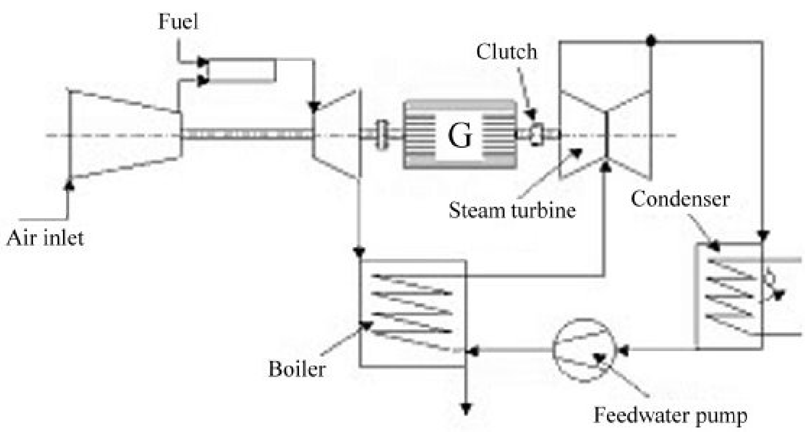

Figure 3: Single shaft combined cycle power plant with one gas turbine and one steam turbine.

A much more flexible configuration is a setup with independent steam turbine and separate generator is shown in Figure 4. This is also usable for retrofit applications, where an existing coal fired boiler is to be replaced by a gas turbine. The main advantage of an installation like this is the possibility to operate the gas turbine totally independently from the steam turbine.

Hence, the power plant can be started up and even operated with the gas turbine only. When the boiler has reached its operation temperature, the steam turbine is started and the steam turbines generator can be synchronized with the net independently.

Such types of power plants with independent shafts can reach very high total efficiency combined with an excellent operational flexibility. On the other hand, this setup has the disadvantage of needing two generators compared to one in a single shaft design. This increases the installation and maintenance costs significantly.

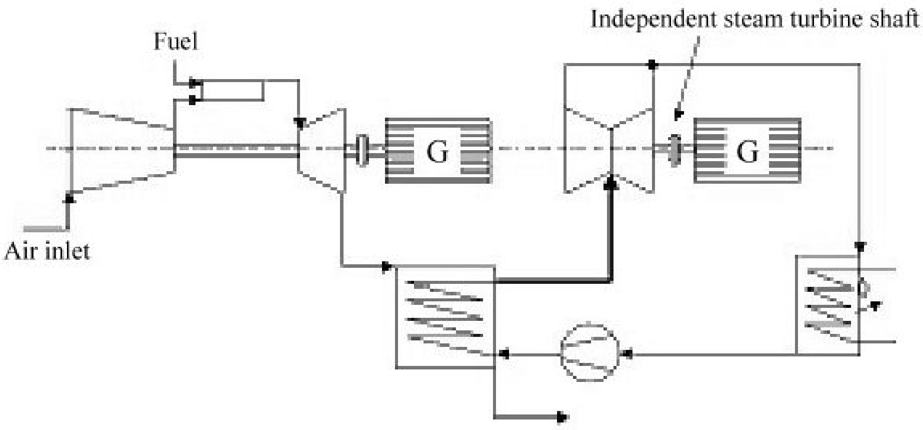

Figure 4: Double shaft, combined cycle power plant with separate generators for gas turbine and steam turbine.

A special form of the described setup is the multi shaft combined cycle power plant like the one shown in Figure 5. Here three gas turbines heat three boilers for one common set of steam turbines. This design is used for big, base load power. This plant setup offers high availability for the plant operation, since the overhaul of a gas turbine can be executed while the plant continues to run on the two remaining gas turbines.

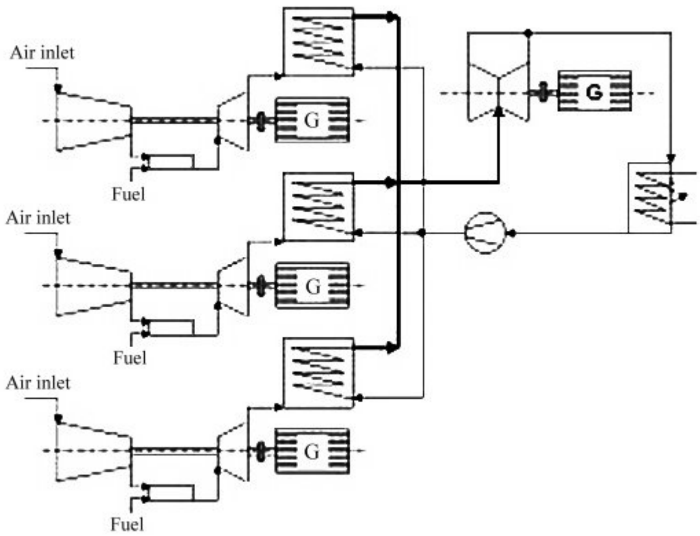

Figure 5: Multi shaft, combined cycle power plant setup.

2. Gas Turbine Components

The typical, ideal working cycle of a continuous flow heat engine is the Joule cycle. It is explained in detail in Section **Error! Reference source not found.**. As a machine working in the Joule cycle, any gas turbine is made out of several characteristic mechanical parts, which will be described roughly in the following sections. Details on the general design of gas turbines and their components can be found in [1] and [2].

2.1. Air Intake

A utility gas turbine, which is used in a power plant, is operated with ambient air as the working fluid. Hence, the air has to be accelerated by the compressor to flow from the environment into the machine. On the way to the compressor the air passes a set of filters to prevent dust from entering the machine. The flow path of the air, the inlet duct, is mostly designed as a diffuser to achieve a deceleration of the flow directly in front of the compressor. Thus, a part of the kinetic energy in the flow is converted into pressure, which is then the compressor inlet pressure.

2.2. Compressor

The compressor can be designed in different ways, depending on the required pressure and the permissible shaft length. There are axial or centrifugal compressors, or a combination of both. An *axial compressor* is a more modern and sophisticated design and has to be built up in several stages to reach the same pressure a centrifugal compressor can reach in one stage. But it has, due to the lower change of flow direction during compression, a much better efficiency.

An axial compressor has the general disadvantage of a long shaft, but is able to handle a much wider range of volume flows. This is because it has a much lower tendency for flow separation at the inlet blades than a *centrifugal compressor*, which makes it more reliable in the case of fast load changes. Thus, axial compressors are used in all heavy utility gas turbines today.

Centrifugal compressors are used only in small gas turbines with high rotor speeds, where a desired small size of the machine determines a short shaft. Combinations of axial and centrifugal compressors are used in some aero-derivative auxiliary power units (APU) to combine the reliability of the axial compressor and the high-pressure ratio of the centrifugal compressor.

Flow separation in the blade grid of the first compressor stage is one of the highest dangers for both, axial and centrifugal compressors. The separation of the airflow from the surface of single blades generates high turbulence in the grid and can partly block the flow path of the incoming air aerodynamically. This effect, called a rotating stall, stresses the whole gas turbine structure with oscillating pressure waves. Another danger for the gas turbine is a deceleration of the machine due to a fast load change, which causes a reverse flow of high-pressurized air into the compressor.

This reverse flow blocks the airflow into the compressor and induces a high-pressure peak, which again stresses the gas turbine structure. The effect, which is known as *compressor stall* or *pumping*, can also be oscillating within the compressor blade rows, which makes things even worse.

The aerodynamic forces in case of a stall are so high that the compressor can be severely damaged. To prevent this bleed valves blow off excessive air to reduce the counter pressure in the compressor at lower rotor speed or frequency conditions.

A possibility to prevent rotating stall as well as compressor stall is to use adjustable inlet guide vanes, which control the airflow through the compressor by optimizing the flow angle of the air to the compressor blades.

Compressors of some heavy gas turbines, which have a high pressure ratio combined with a high mass flow, are using both options to be able to run the compressor always in the optimum operation mode.

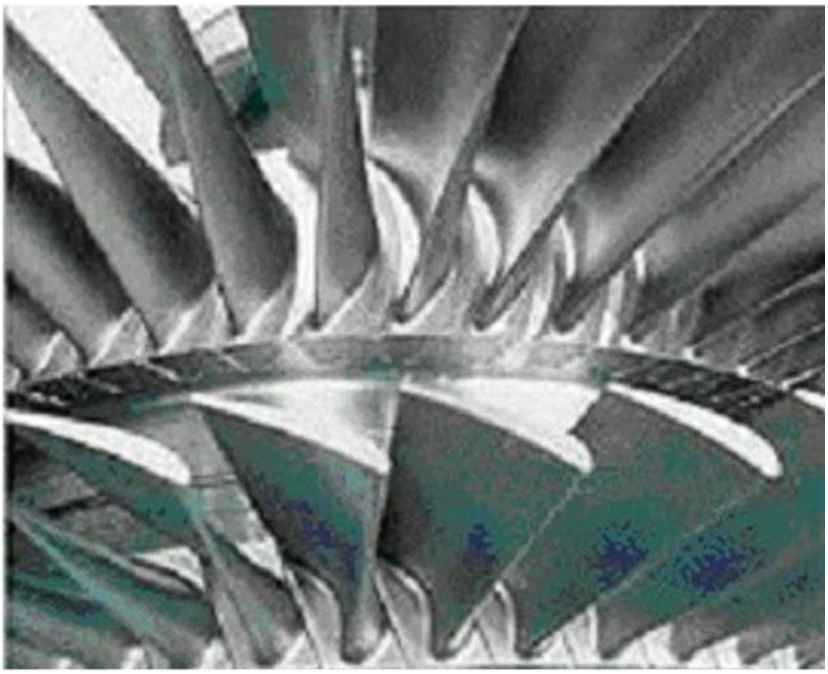

Figure 6: Compressor blades of a heavy-duty gas turbine.

2.3. Combustor

The heat supply to the working cycle happens in the combustion chamber, where liquid or gaseous fuel is oxidized with the compressed air in a continuous combustion process. In praxis several combustor designs are in use, depending on the manufacturer, type of gas turbine, fuel and load requirements. Thus, to understand the different combustion chamber designs, one has to remind the basics of gas turbine combustion.

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Biographical Sketches

Hans-Kaspar Scherrer, was born in 1962 and received a degree in Mechanical Engineering from ETH Zurich and a Doctor degree in Mechatronics and Robotics also from ETH Zurich. Main topics and contributions during these studies were systems dynamics, controls, system integration and fast, multivariable control systems, e.g. for an artificial hand of a robot.

In 1994 the Author joined at ABB Power Generation Ltd in Switzerland as a Control and System Engineer and was responsible for the development of an advanced Gas Turbine Control System for a new Gas Turbine with sequential combustion. The development was completed with onsite testing and verification of the control systems during a 12 month test phase. In 1997 the Author became responsible for the development organization of power plant control products such as gas turbine controllers, steam turbine controllers, combined cycle power plant control systems, advanced monitoring and optimization systems and operating training simulators.

Christopher Ganz was born in 1963 and received a degree in Electrical Engineering from ETH Zurich and a Doctor degree in Automatic Control also from ETH Zurich. Research topics covered computer aided control systems design, real-time software development, and power system stability.

In 1995 the Author joined ABB Power Generation Ltd in Switzerland as project manager for the development of plant management software, i.e. operator station software for power plants in an international project. In 1996 the author was involved in gas turbine simulation and control design, and later in software development for power plant control. Today, the author is responsible for the product management organization for power plant automation, which includes turbine control, advanced monitoring and optimization software, waste to energy automation products, and operator training simulators.

Wolfgang Weisenstein was born in Bad Oeynhausen, Germany, in 1962. He received a degree in mechanical engineering, specializing on combustion in jet propulsion engines, at the Fachhochschule Aachen, Germany, in 1990. After 10 years of experimental combustion research on different subjects at ABB Corporate Research Ltd. the author received a degree in computer science at the Fachhochschule Zurich, Switzerland, in 2000. Since May 2000 he works as a development project manager at ABB Switzerland, Div. Utility Automation. His primary interest is the development of diagnosis and control software for combustion optimization in utility gas turbines. He is member of the *American Institute of Aeronautics and Astronautics (AIAA)* and of the *American Society of Mechanical Engineers (ASME)*.